Quarks and gluons in and through the nucleus

Alberto Accardi
Hampton U. and Jefferson Lab

JLab at 12 GeV: New opportunities in hadronic physics
LNF, Frascati
18 December 2012

"The coherence provided by QCD means that insights [into hadron and nuclear structure] may arise from unexpected quarters.

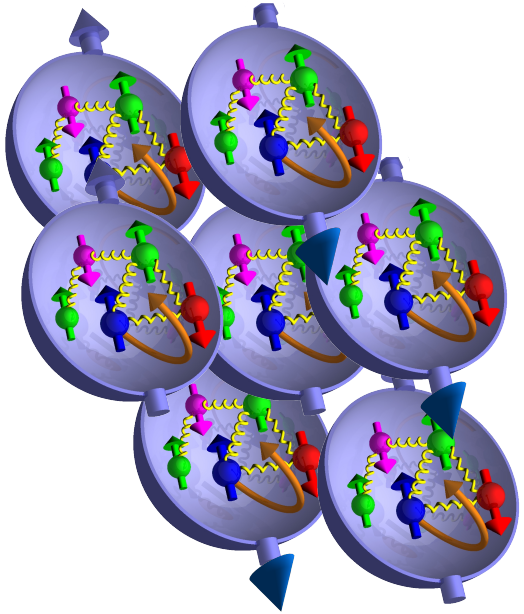
It is more than ever advisable to take a broad view that integrates across hadronic physics, and to connect with the rest of subatomic physics."

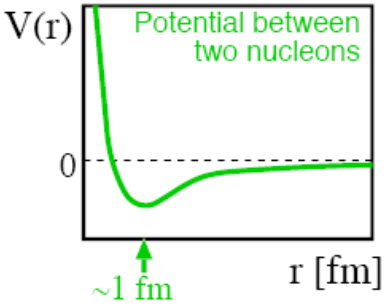
C. Quigg, 2011

"The Future of Hadrons: The Nexus of Subatomic Physics"
Talk at "Hadron 2011", arXiv:1109.5814

Nucleon and nucleus structure

$$L_{QCD} = \bar{q}(i\gamma^\mu \partial_\mu)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu}$$





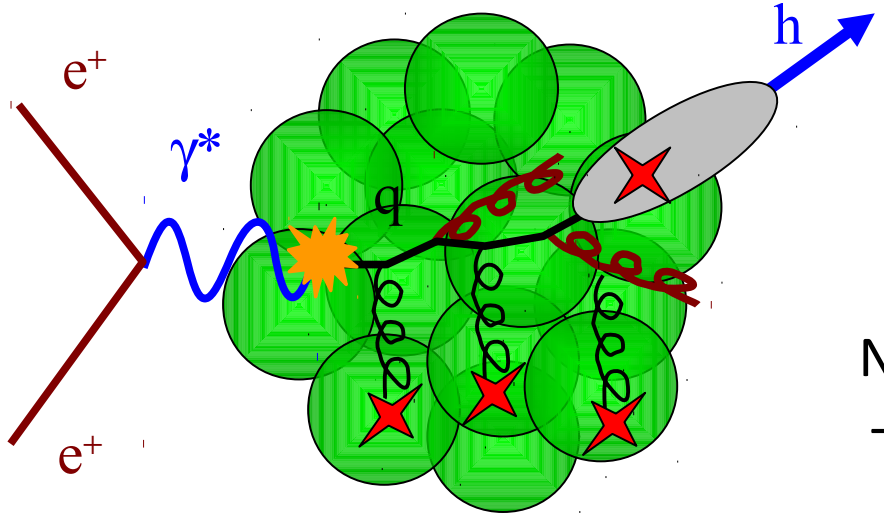
How do gluons bind quarks and gluons?

How do nuclei emerge from QCD?

- what generates the repulsive potential?
- how are nucleons modified?
- what is the role of nuclear gluons?

The nucleus as a QCD laboratory

$$L_{QCD} = \bar{q}(i\gamma^\mu \partial_\mu)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu}$$



Nucleus as space-time analyzer:
- hadronization dynamics
  "confinement in action"
- quark energy loss

Nucleus as a filter:
- color transparency

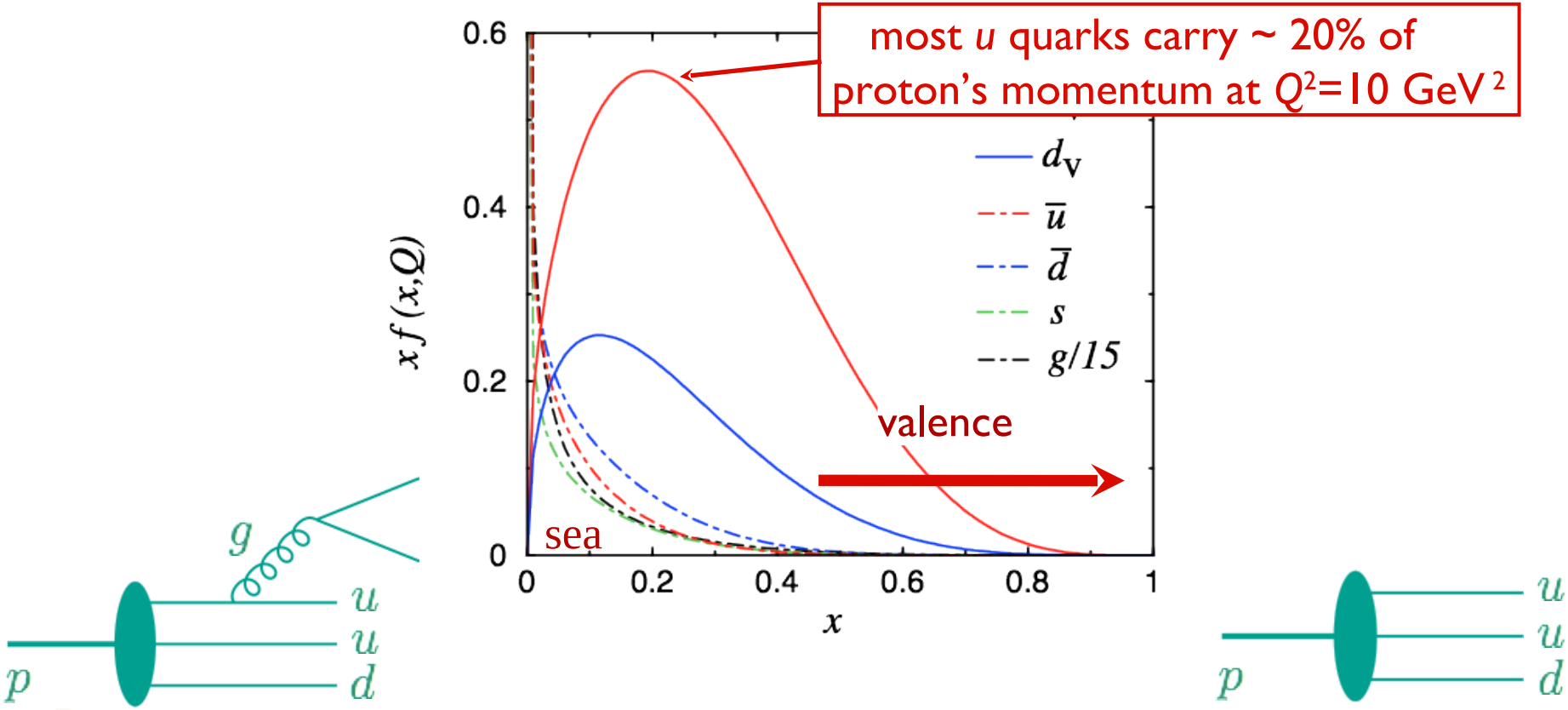
Electron as charged probe of quarks (and hard gluons)

Struck quark as internal colored probe of soft gluon matter

Quarks in the deuteron

Valence quarks at large *x*

- Most direct connection between quark distributions and models of nucleon structure is via valence quarks
  - Most cleanly revealed at $x > 0.4$



Valence quarks at large *x*

- At large *x*, valence *u* and *d* extracted from *proton* and *neutron* DIS structure functions

$$F_2^p \approx \frac{4}{9} u_v + \frac{1}{9} d_v$$

$$F_2^n \approx \frac{1}{9} u_v + \frac{4}{9} d_v$$

  - *u* quark distribution well determined from proton data
  - *d* quark distribution requires neutron structure function

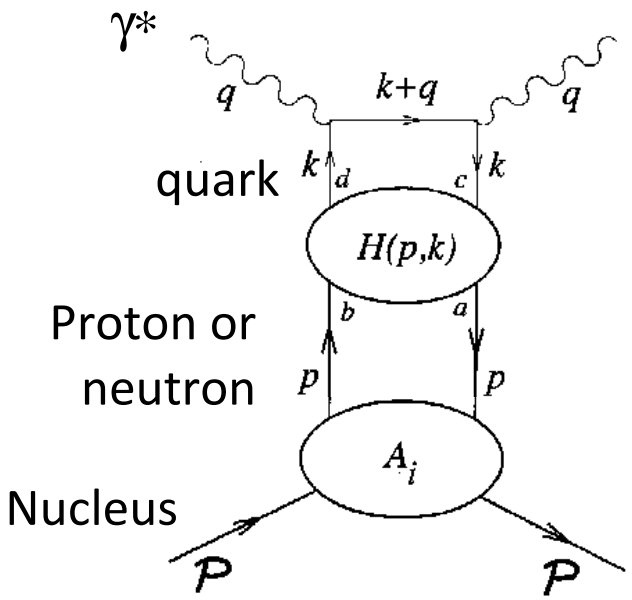
$$\frac{d}{u} \approx \frac{4F_2^n/F_2^p - 1}{4 - F_2^n/F_2^p}$$

But… deuteron corrections!

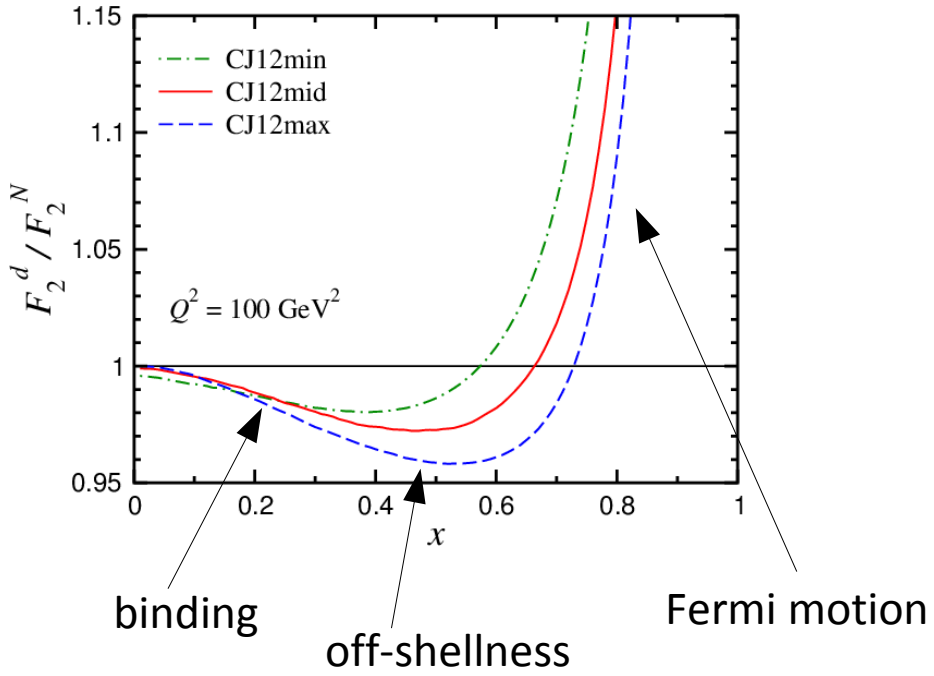
Owens, AA, Melnitchouk, arXiv:1212.1702

- No free neutron! Best proxy: Deuteron
  - Parton distributions (fitted)
  - nuclear wave function (AV18, CD-Bonn, WJC1, …)
  - Off-shell nucleon modification (model dependent)

Theoretical uncertainty



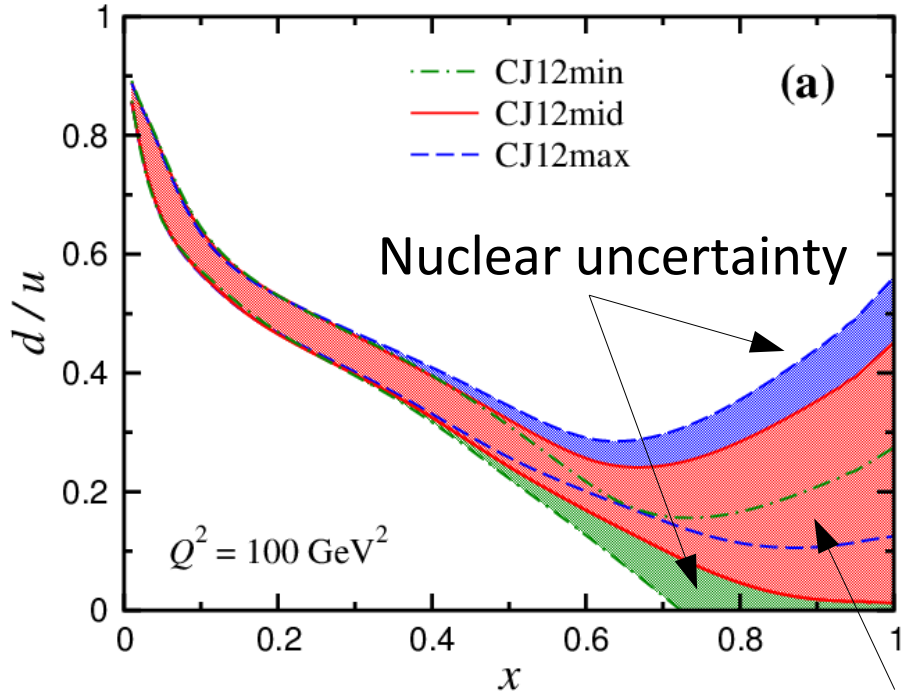
Bound vs. free proton+neutron



Nuclear uncertainty from a global PDF fit

Owens, AA, Melnitchouk, arXiv:1212.1702

- CJ12: CTEQ-JLab global parton distributions fit
  - Data: DIS on p,d (fixed target and HERA); DY, jets and γ+jet (Fermilab)
  - Extrapolates $d/u \xrightarrow[x\to 1]{} 0.22 \pm 0.20\,(\mathrm{PDF}) \pm 0.10\,(\mathrm{nucl})$



Non-perturbative proton models

SU(6) spin-flavor

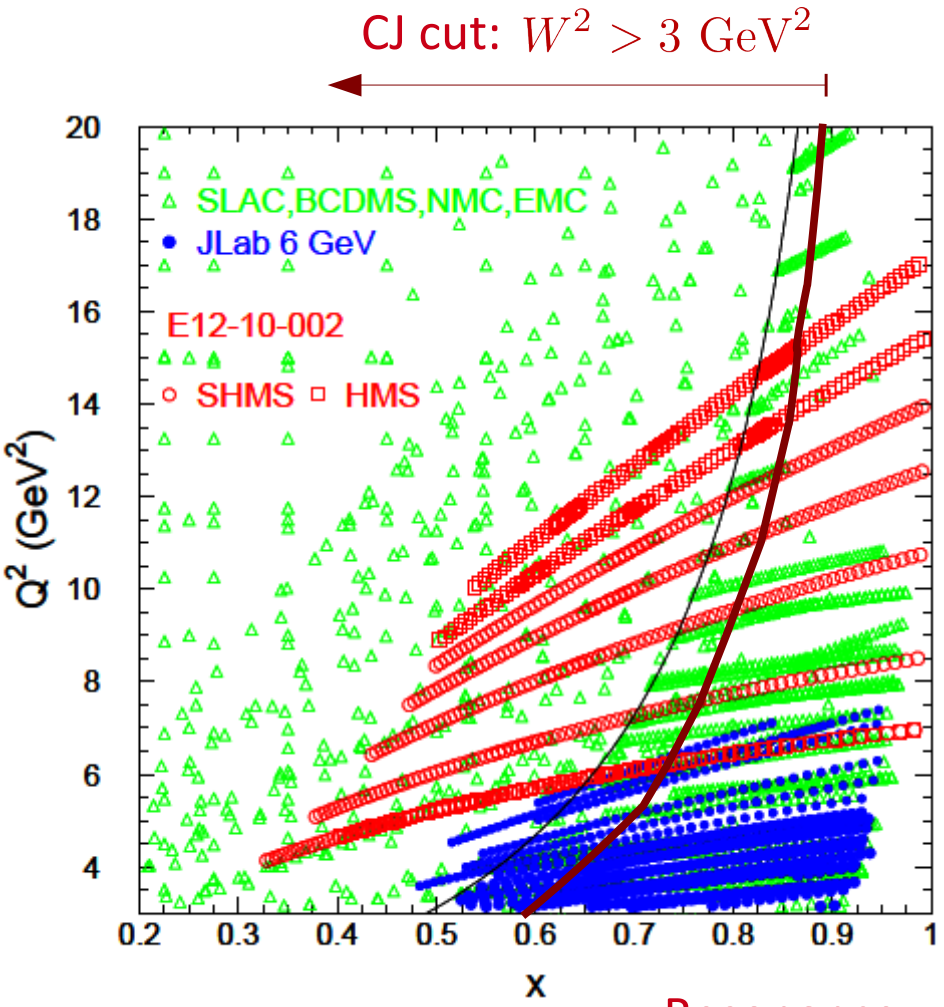
hard gluon exchange

S=0 diquark dominance

"PDF" experimental uncertainty

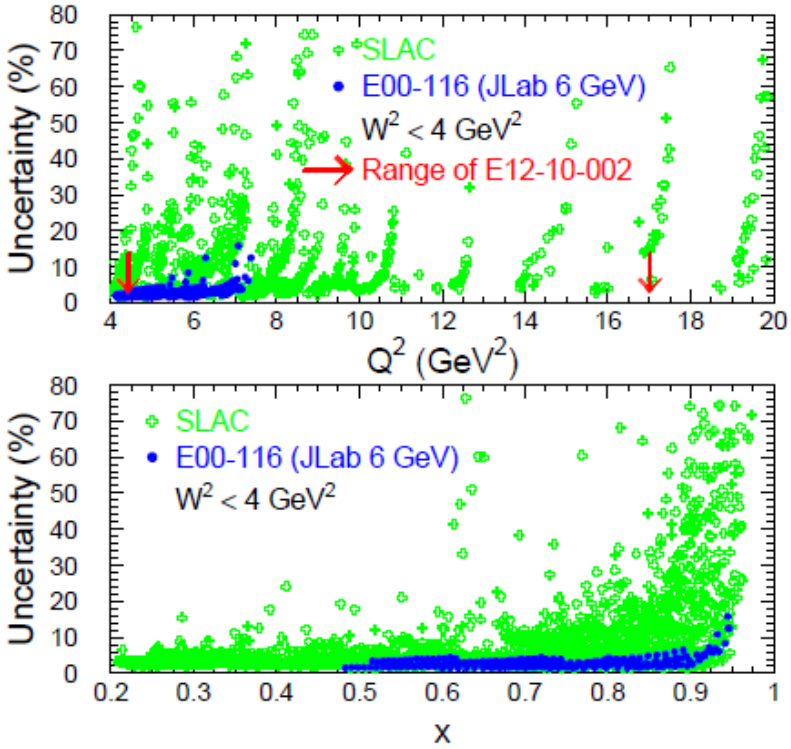
Beating the experimental uncertainty

Jlab12 experiment E12-10-002



DIS region

Resonance region



Goal @ 12 GeV:
similar precision as
E00-116 (@ 6 GeV)

Constraining the nuclear uncertainty

- **Data minimally sensitive to nuclear corrections**
  - DIS with slow spectator proton (BONUS, **BONUS12**)
    - Quasi-free neutrons
  - DIS with fast spectator (DeepX, **LAD**)
    - Off-shell neutrons
  - ^{3}He/^{3}H ratios (**MARATHON**)

JLab

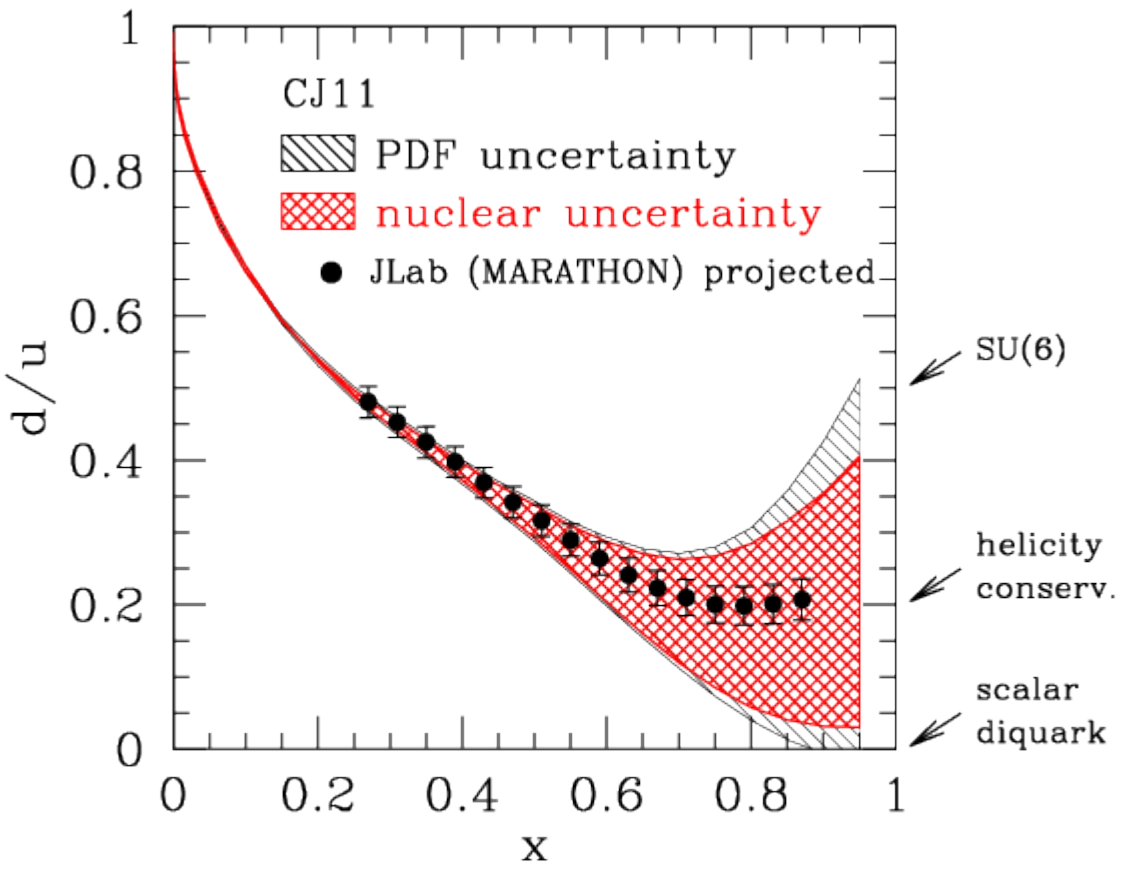
- **Data on free (anti)protons, sensitive to *d* or *g***
  - *e+p*: F_L , parity-violating DIS **JLab12 , HERA** *(e^++p vs. e^-+p)*
  - ν+*p*, ν+*p*
  - *p+p, p+*$\bar{p}$ at large positive rapidity
    - *W* charge asymmetry, *Z* rapidity distribution

Tevatron: D0, CDF??
LHCb?? RHIC ??
AFTER@LHC

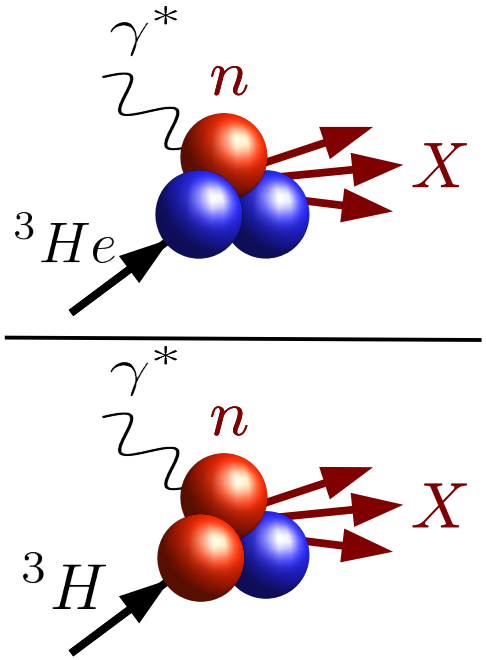
- **Cross-check data**
  - *p+d* at large negative rapidity – dileptons; *W*, *Z*
    - Sensitive to nuclear corrections, cross-checks *e+d*

RHIC ??
AFTER@LHC

Quasi-free neutrons from MARATHON



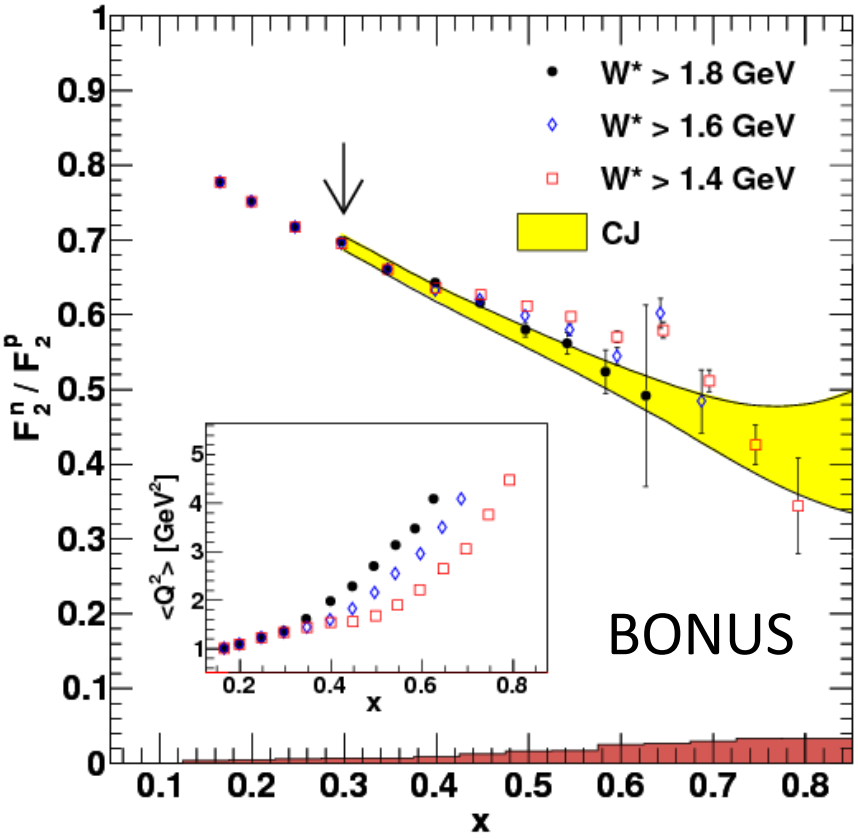
JLAB12 experiment E12-10-103

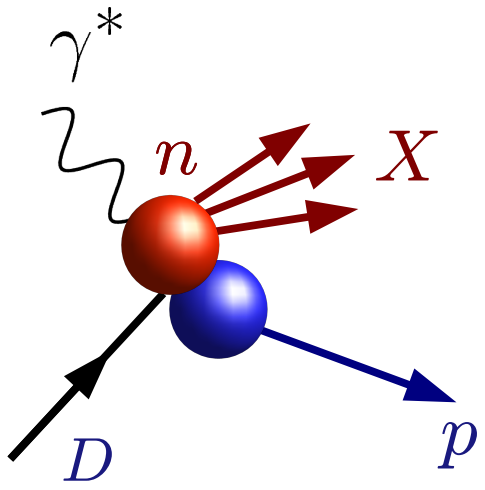


- Nuclear corrections largely cancel in the ratio of ^{3}He/^{3}H cross sections
  - Fermi motion will somewhat limit the actual large-*x* reach

Quasi-free neutrons from BONUS

N.Baillie et al., PRL 108 (2012) 199902

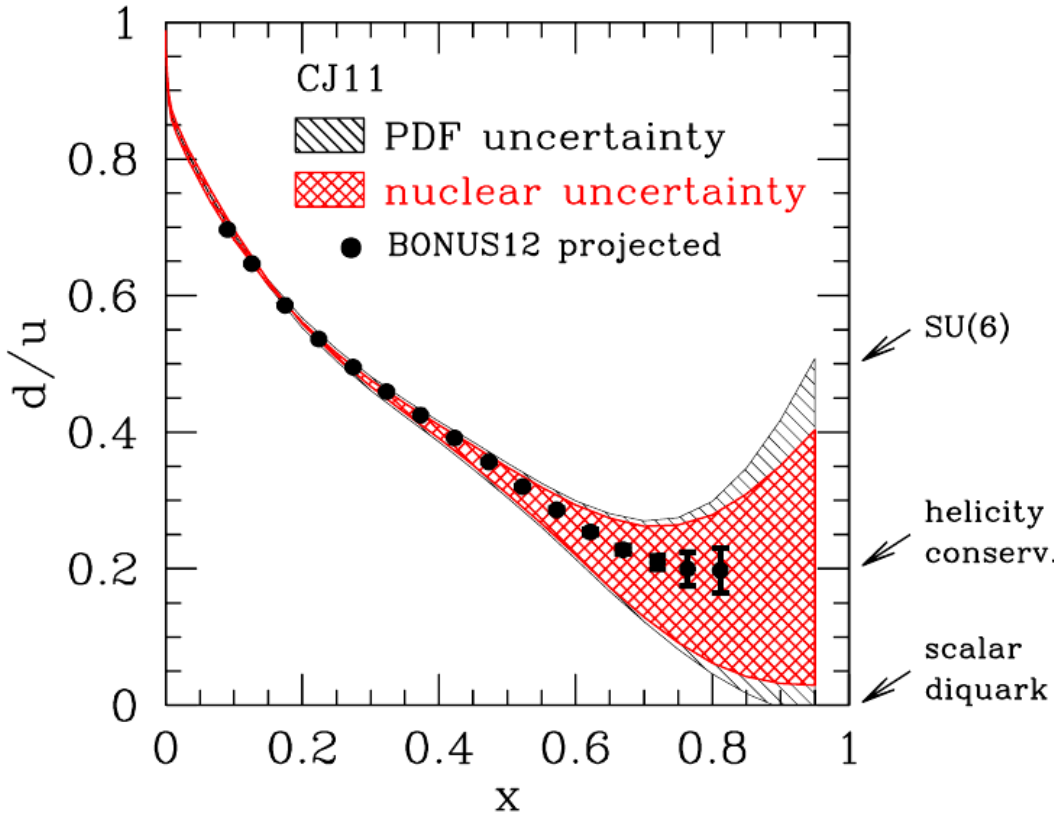


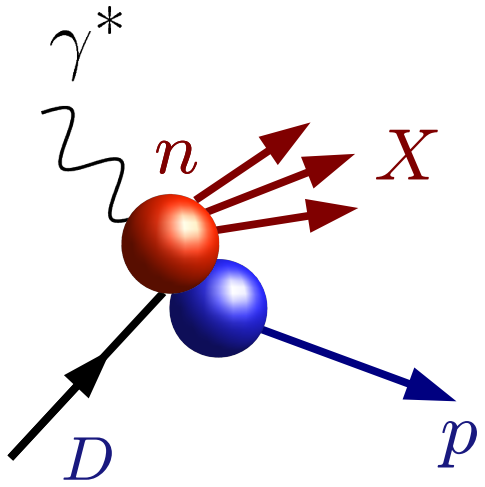


- DIS data (black disks) too uncertain at $x > 0.5$

Quasi-free neutrons from BONUS12

Approved Jlab12 experiment



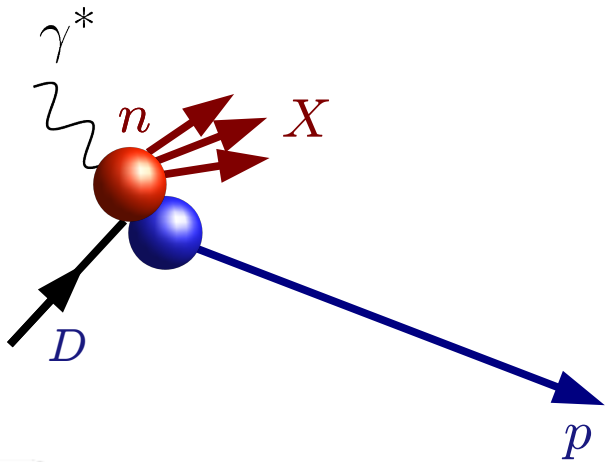


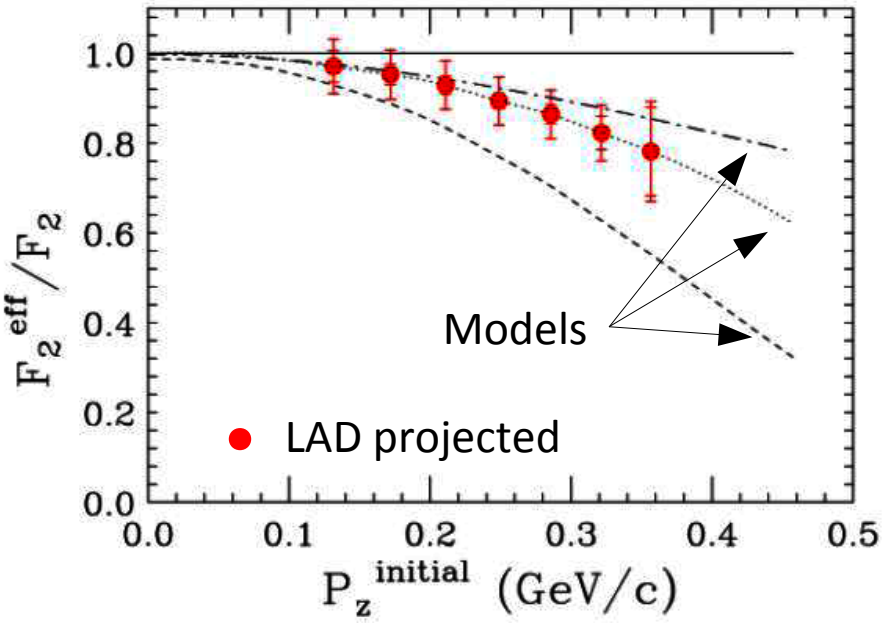
- DIS data (black disks) too uncertain at $x > 0.5$

Off-shellness and in-medium modifications

LAD (E12-11-107) at JLab 12

- Neutron off-shellness depends on on spectator momentum:
  - Slow: nearly on-shell (BONUS12)
  - Fast: more and more off-shell (LAD)

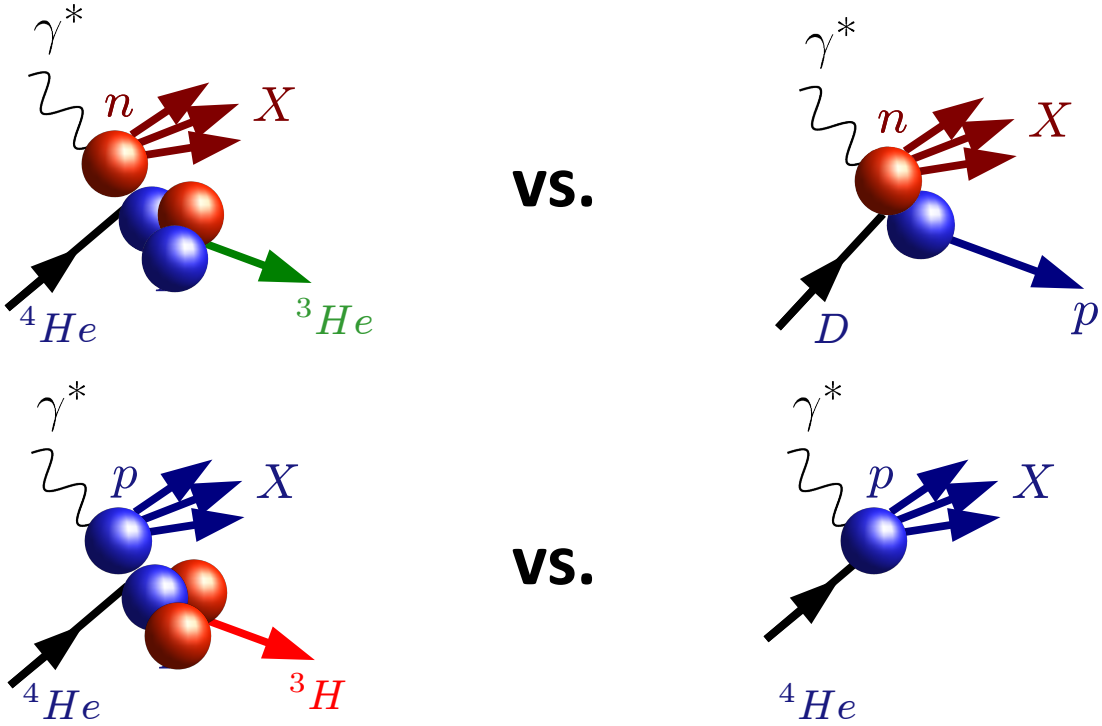




Off-shellness and in-medium modifications

data on tape from EG6 at Jlab6,
possible at Jlab12 (e.g., LOI-10-009)

- Why stopping here?
  - **Proton and neutron in light nuclei:**
    embedding in nuclear matter **(a piece of the EMC puzzle)**

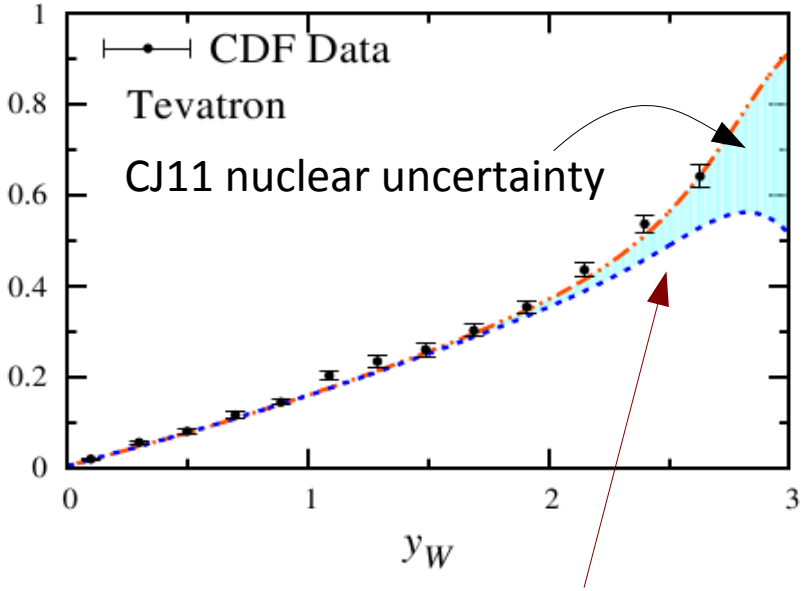


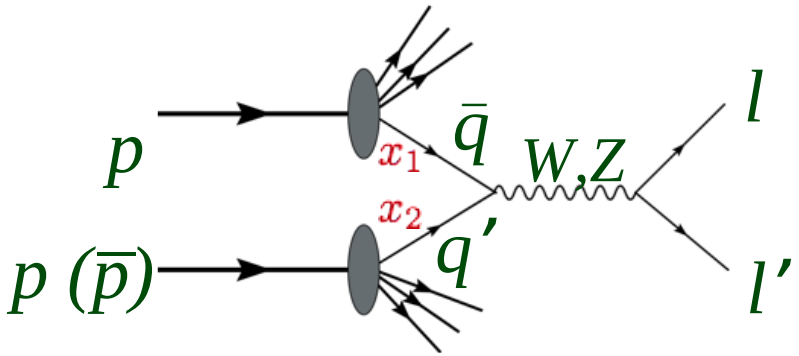
W charge asymmetry at Tevatron (p+p collisions)

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

Directly reconstructed W:

- highest sensitivity to large *x*





$$A_W(y) = \frac{\sigma_(W^+) - \sigma_(W^-)}{\sigma_(W^+) + \sigma_(W^-)} \approx \frac{d/u(x_2) - d/u(x_1)}{d/u(x_2) + d/u(x_1)}$$

sensitive to *d* at high *x* → Can constrain Nuclear models!

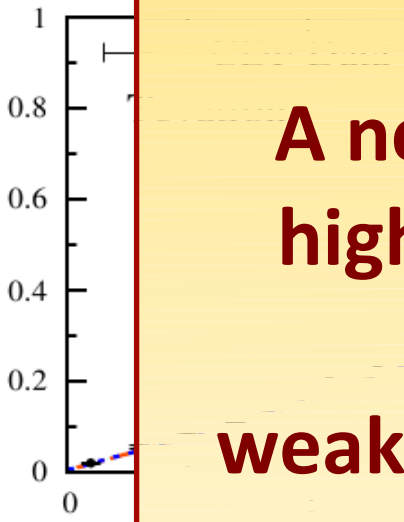
- Needs to be corroborated:
  - **PVDIS at JLab 12 [SOLID (E12-10-007)]**, *Z* at LHC, *W* at DØ

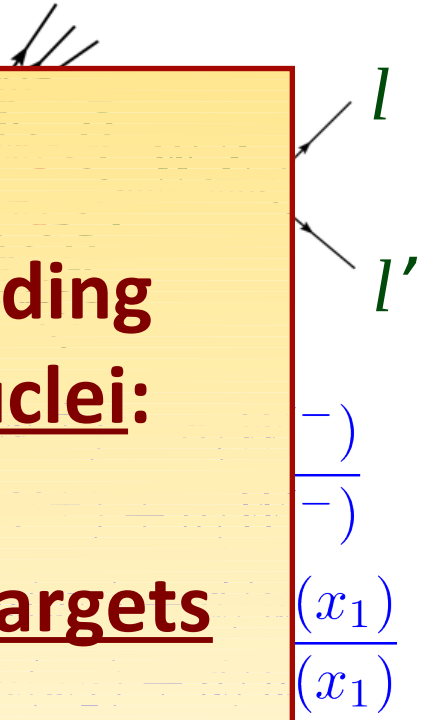
W charge asymmetry at Tevatron (p+p collisions)

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

Directly reconstructed W:

- high





A new avenue for understanding high-energy processes on nuclei:

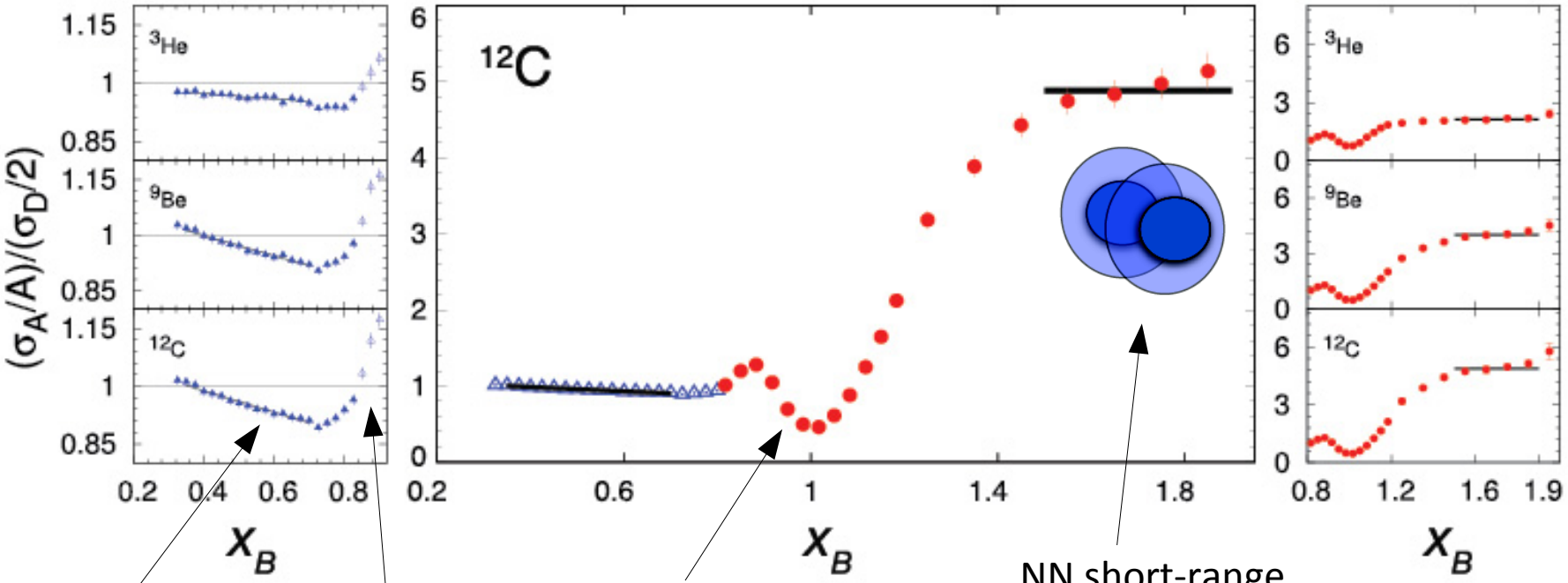
weak interactions on proton targets from JLab to the LHC!

- Needs to be corroborated:
  - **PVDIS at JLab 12 (SOLID E12-10-007)** , Z rapidity at LHC, W at D0

EMC effect and short range correlations

Nuclei at large x

- **EMC effect:** quark nuclear modifications, a puzzle since 30+ years
- **Scaling at x_B>1:** "Short Range Correlations"



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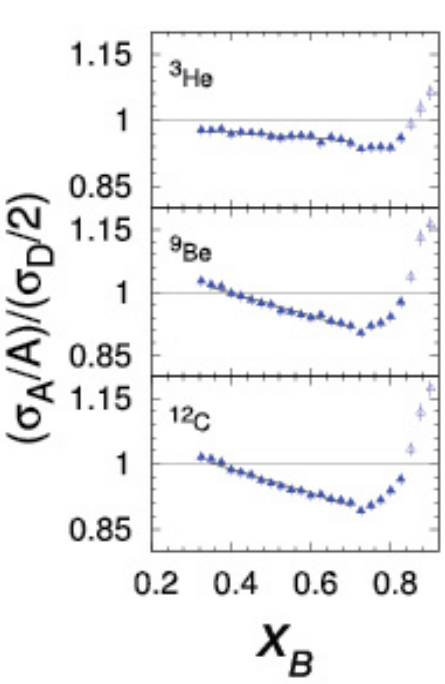
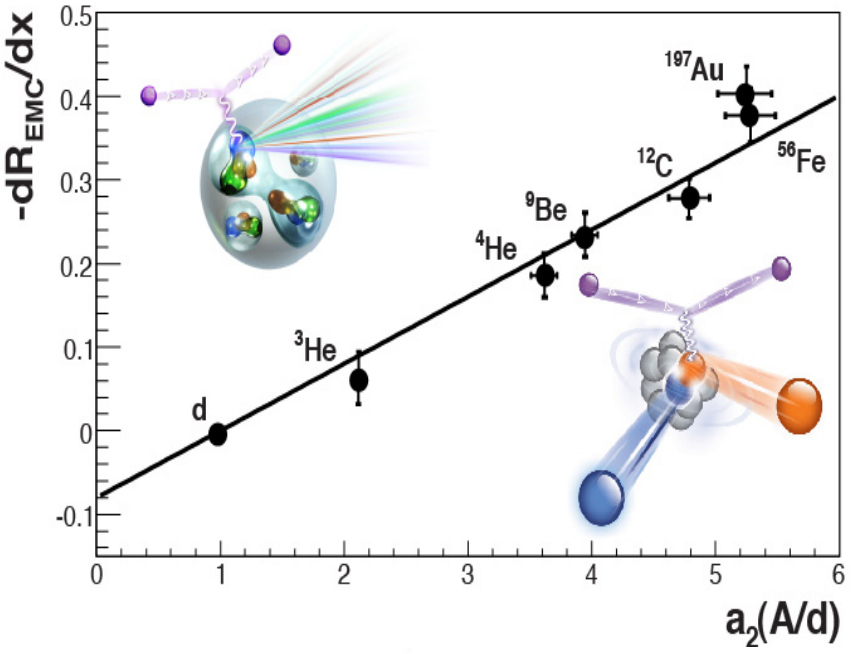
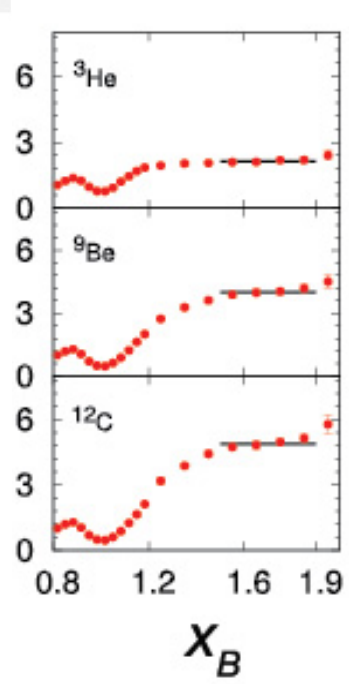




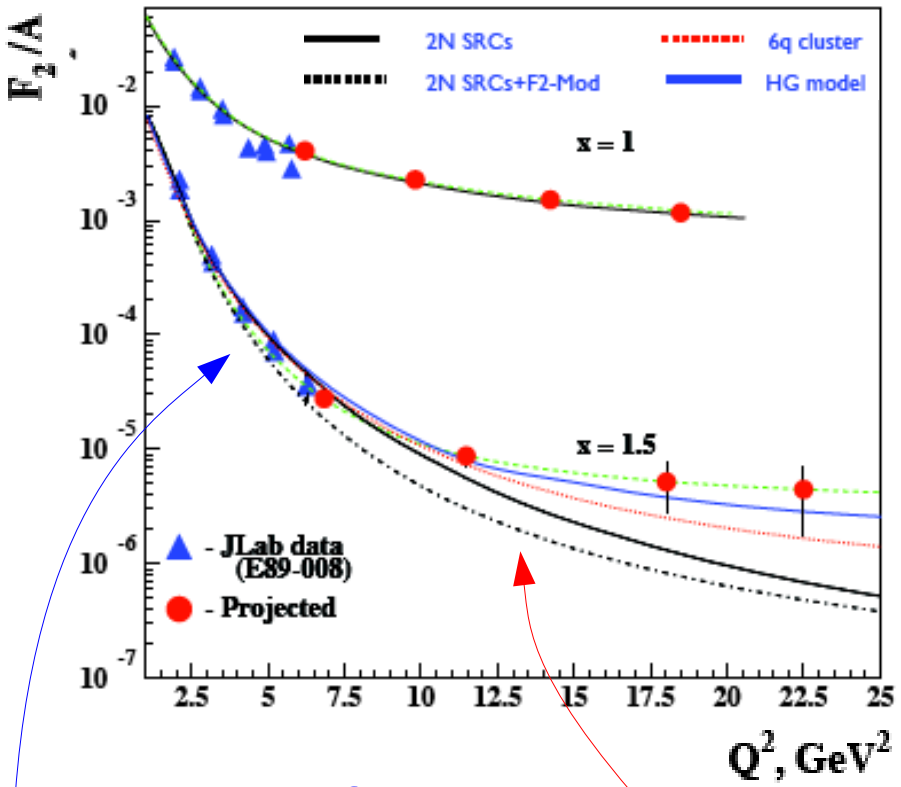


These are correlated: common physics origin?

At JLab12: superfast quarks

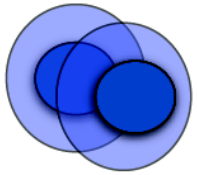
JLab 12 experiments E12-06-105, E12-11-112

Sargsian et al., JPG29 (2003)



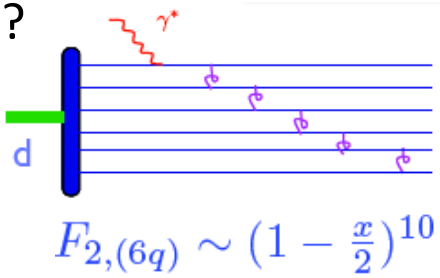
Quark in faster-than-average nucleon:

- Short-range *NN* potential
- Very off-shell nucleons



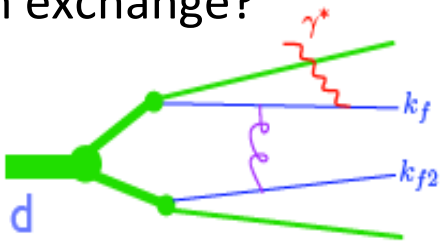
Scattering on exotica:

- 6-quark bags?



Novel QCD mechanisms:

- Hard-gluon exchange?



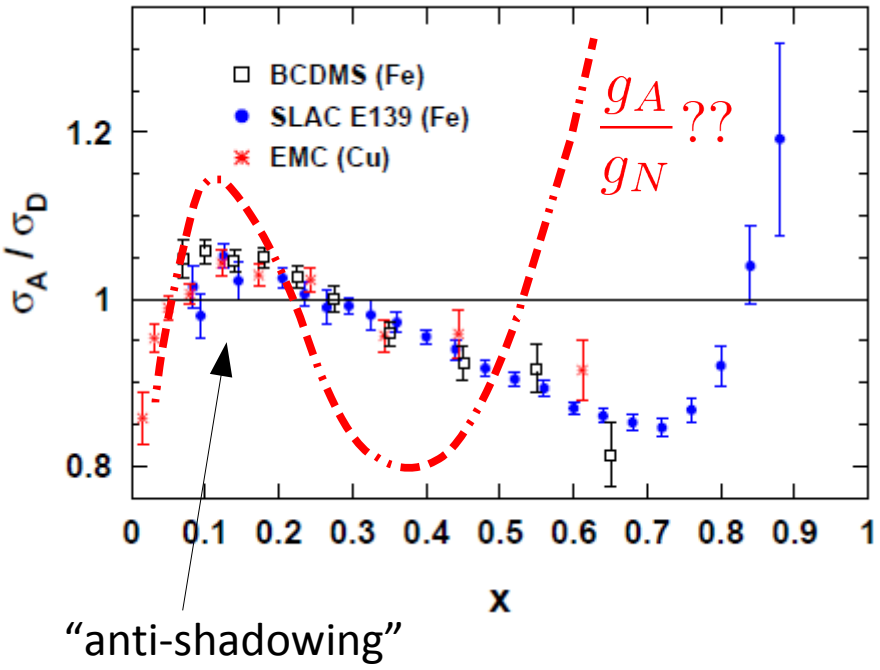
6 GeV, small Q^2
⇒ Quasi-elastic on nucleons

12 GeV, large Q^2
⇒ DIS on quarks

Gluons in nuclei

Guzey et al., arXiv:1207.0131 (to appear in PRC)

- **Next to nothing known about large-x nuclear gluons**
  - In fact, indications that "anti-shadowing" resides in longitudinal cross section the sketch may be qualitatively correct!
  - **Needs dedicated nuclear L/T separation at 12 GeV**
    [PR10-010 – to be resubmitted to next PAC]

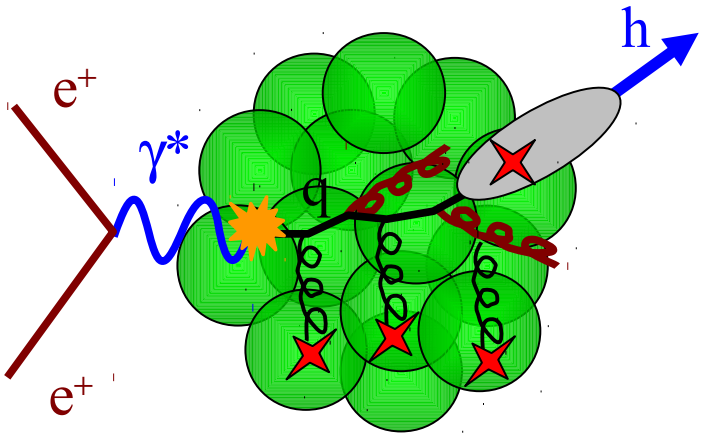


Quarks through the nucleus

Parton propagation and fragmentation

Review: Accardi et al., Riv. Nuovo Cim. 032,2010

- **Nuclei as space-time analyzers**



Transverse momentum broadening

$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

Hadron attenuation

$$R_M = (N^h/N^e)_A/(N^h/N^e)_D$$

Small ν $\Rightarrow$ hadronization inside

Large ν $\Rightarrow$ hadron boosted outside, quark propagation in nuclei

- **Non perturbative aspects**
  - Color confinement dynamics
  - Probe soft nuclear gluons
- **Perturbative QCD**
  - testing pQCD energy loss

Parton propagation and fragmentation

Review: Accardi et al., Riv. Nuovo Cim. 032,2010

- **Nuclei as space-time analyzers**

Transverse momentum broadening

$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

Hadron attenuation

$N^e)_D$

de

utside,

in nuclei

Partons created in the medium can be used as color probes of nuclear gluons when parton lifetime and energy loss mechanisms are under theoretical control

- **Non perturbative aspects**
  - Color confinement dynamics
  - Probe soft nuclear gluons
- **Perturbative QCD**
  - testing pQCD energy loss

Nuclear color field ("gluonic matter")

B. Mueller, talk at Confinement X, Munich 2012

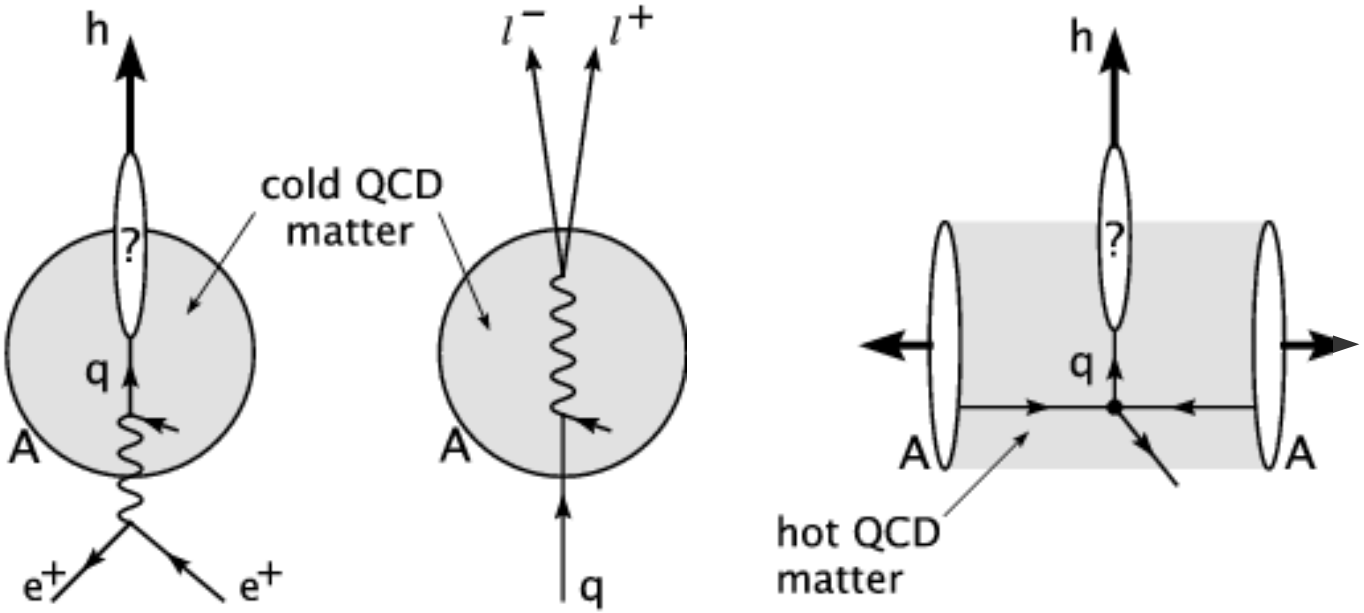
- DIS: known and static medium density
  - Quarks couple to soft (small-x) gluons
  - Attenuation, pT-broadening, induced gluon radiation governed by **"transport coefficients"**
  - **Fundamental gluon field correlators**

$$\left.\begin{aligned}
\hat{q} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^- \left\langle U^\dagger F^{a+i}(y^-)UF_i^{a+}(0)\right\rangle \\
\hat{e} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^- \left\langle iU^\dagger \partial^- A^{a+}(y^-)UA^{a+}(0)\right\rangle \\
\kappa &= \frac{4\pi\alpha_s}{3N_c}\int d\tau \left\langle U^\dagger F^{a0i}(\tau)t^a UF^{b0i}(0)t^b\right\rangle
\end{aligned}\right\}$$

Momentum / energy diffusion

Cold and hot nuclear matter

Review: Accardi et al., Riv. Nuovo Cim. 032,2010



DIS

FS energy loss

+ hadronization

DY

IS energy loss

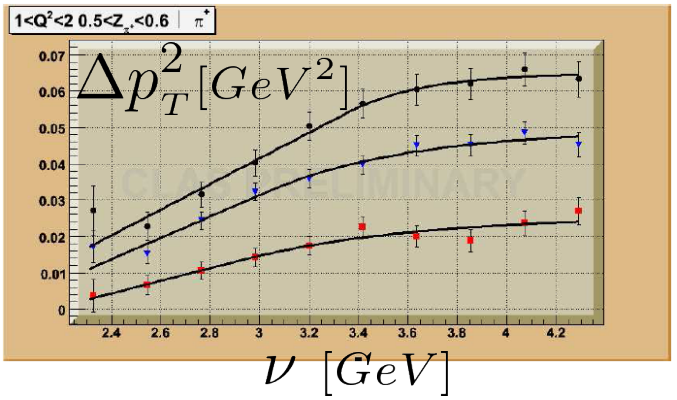
+ nuclear PDFs

properties of the QGP

DY vs. EMC effect

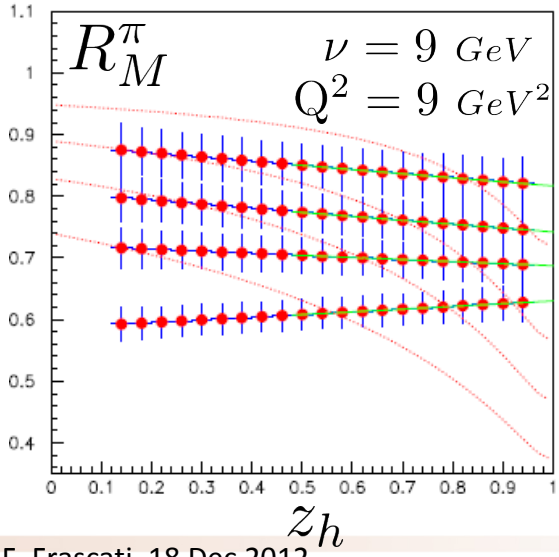
Hadronization at HERMES and JLab

- **HERMES:**
  - first precise flavor separation (π,K,p), 2D distributions



- **JLab 6:**
  - preliminary 3D pions, first η , K_0 ever
  - Preliminary indications of long quark lifetime

- **JLab 12 – E12-06-117:**
  - Up to 5D distributions
  - Multiple flavors
  - More leverage in ν, Q^2



Summary

- **Jlab at 12 GeV will**
  - study the QCD structure of nuclei
  - use the nucleus as a laboratory to study QCD
  - investigate fundamental issues in modern nuclear physics
- **Nature of the nucleon-nucleon interaction at short distances**
  - nucleons and mesons, or quarks and gluons?
- **Quark-gluon structure of bound nucleons**
  - How does this relate to the short-distance NN wave function?
  - Wide ranging impact, up to LHC
- **Quark propagation and hadronization in cold nuclear matter**
  - Confinement in action
  - Nuclear non-abelian color fields
    - "gluon matter", "color glass condensate"

The future: the Electron-Ion Collider

Medium-energy EIC science review:
Accardi et al., Eur.Phys.J. A48 (2012) 92

- **Larger energy:**
  - Sea quarks and gluons
  - Gluon saturation at small *x*
  - Heavy quarks
  - Jets in e+p, first time in e+A
  - Rich quark propagation and hadronization program

- BNL and Jlab designs

"MEIC @ Jlab conceptual design"

Abeyratne, Accardi, Deconinck, et al.
arXiv:1209.0757

Appendix: last but not least…

- **Topics not covered in this presentation:**
  - **Color transparency**
    - Small q-qbar and qqq QCD configurations
  - **Nuclear spin distributions, TMDs, GPDs**
  - **Neutron skin of the nucleus**
    - Implications for neutron stars